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AUG 76 W S DAVIS, D GRETZ, J RICHARD N00014-76-C-0428

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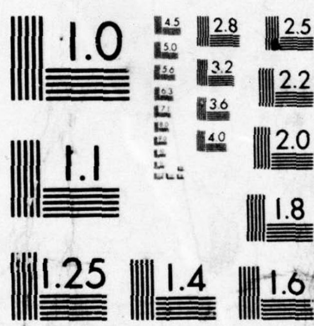

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ANNUAL REPORT

NOISE MEASUREMENTS OF THE LOWEST FREQUENCY LONGITUDINAL MODE OF AN ALUMINUM CYLINDER AT LIQUID NITROGEN TEMPERATURES

Report prepared by
Wm. S. Davis

Research Conducted by
Wm.S. Davis, D. Gretz, J-P. Richard, G. Rydbeck, J. Weber

August, 1976

UNIVERSITY OF MARYLAND
DEPARTMENT OF PHYSICS AND ASTRONOMY
COLLEGE PARK, MARYLAND

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The cylinder appeared to have attained thermal equilibrium after its temperature had been maintained near liquid nitrogen temperatures for several weeks. Noise temperatures within a factor 2 of the temperature measured by a

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The very large fluctuations in noise temperature are not understood and warrant further investigation.

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The lowest frequency longitudinal mode of an aluminum cylinder has been studied over the temperature range 60°K - 78°K. Lead zirconate titanate crystals were bonded to the cylinder for observation of the thermal fluctuations, and relaxation phenomena. Large amounts of excess noise were observed whenever the cylinder was not in thermal equilibrium.

The cylinder appeared to have attained thermal equilibrium after its temperature had been maintained near liquid nitrogen temperatures for several weeks. Noise temperatures within a factor 2 of the temperature measured by a platinum resistance thermometer were observed when the mean temperature of the cylinder was drifting less than 0.01° Kelvin per day.

The very large fluctuations in noise temperature are not understood and warrant further investigation.

I. INTRODUCTION

A cryostat has been designed and built for the study of low frequency phonons at liquid helium temperature. As a test of the apparatus an eight inch diameter by sixty inches long aluminum bar with piezoelectric transducers was installed and cooled with liquid nitrogen. The performance of the cryostat and the acoustic isolation was observed. Also it was desired to observe the time that a suddenly cooled large elastic solid would take to approach thermal equilibrium.

The cryostat operated well. The 150 liter dewar held liquid nitrogen for about three months. The noise temperature approached the thermal temperature to within $\pm$ 50%, the error attributed to the measurement process. Excess noise, eg. acoustic leakage and nonequilibrium, was not observed above this error. At the time the first such measurements were made the bar had been below 80°K for three weeks and below 300°K for six weeks.

II. BRIEF DESCRIPTION OF APPARATUS

The cryostat and piezoelectric transducers are described in detail by Darrell Gretz.[1] A brief description follows. Two pzt-8 ferro-electric ceramic crystals were cemented together between two aluminum blocks, the latter then cemented to the top of the 8" by 60" aluminum bar. Urethane rubber was used as the bond. The bar rested on a "knife edge" support developed by J.P. Richard.[2] These in turn rested upon alternate layers of felt and iron for acoustic isolation. A platinum resistor was cemented to one of the iron plates to have a temperature measure approximating that of the bar. Surrounding this was a dewar with superinsulation and a vapor shield with superinsulation, all inside a vacuum tank. There was just one common vacuum space for the system which was kept evacuated with an oil diffusion pump.

---

1. Gretz, Darrell, "Development of Four Degree Kelvin Gravitational Radiation Detectors." U. of Maryland Technical Report No. 75-090.

2. Richard, J.-P., "Sensor and Suspensions for a Low-Temperature Gravitational Wave Antenna," Rev. Sci. Instr., 47, 423.

III. CRYOSTAT OPERATION

After leaks were repaired, one week was required for pumping the vacuum tank to less than half a micron. Liquid nitrogen was then added to the dewar and cooldown begun. Table I shows the history of the experiment from the beginning of cooling. With liquid nitrogen in the dewar the pressure in the vacuum tank was less than .05 microns, except when helium gas was intentionally added. This was done during cooldown to increase the thermal conductivity between the bar and the dewar. About five microns of helium gas was used, roughly the pressure at which the thermal conductivity of the gas between the bar and the dewar becomes independent of pressure.

It took 25 days to cool from room temperature to 78°K. Over the next three months, noise and equivalent circuit measurements were made at this temperature and about a hundred liters of liquid nitrogen were consumed. Next a rotary pump was attached to the output of the cryostat and the liquid nitrogen was pumped on to lower its temperature. A pressure gauge was attached so that the dewar pressure (and thus the liquid nitrogen temperature) could be measured when the pump was valved off. The following data were adapted from Applied Cryogenic Engineering by Vance and Duke:

Temperature (°K)	Nitrogen Equilibrium vapor pressure (mmHg)
77.4	760
66	154
64	109
63.14 (triple point)	96
62	74
60	47
56	18
52	6

TABLE I

THERMAL HISTORY

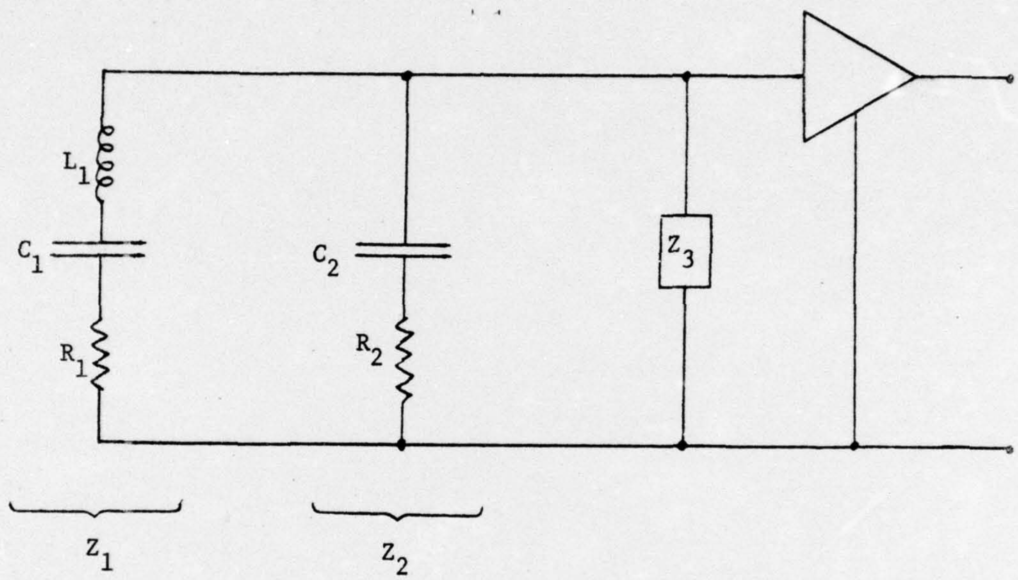
Date	Temperature (°K)	Comments
July 3	300	Start cooling
July 9	200	He gas added to tank
July 16	90	
July 23	80	600ℓ liq. N_2 added since start
July 28 through Oct. 26	78	tank evacuated, more liq. N_2 added
Oct. 27	78	Begin pumping on Liq. N_2, He gas added to tank
Nov. 5	60	tank evacuated
Nov. 12 through 26	62	
Dec. 2 through 10	64	
Dec. 22	66	liq. N_2 gone
Christmas break		water failure
Jan. 5,1976	165	
Jan. 7	170	Start recooling
Jan. 9	160	He gas added to tank
Jan. 13	112	
Jan. 19	82	350 ℓ liq. N_2 added since start of recording
Jan. 23 through Feb.4	78	tank evacuated
Feb. 5	78	Begin pumping on liq. N_2, He gas added to tank
Feb. 13	62	tank evacuated
March 11 through April 9	66	
April 10	66	liq N_2 gone
April 15	75	N_2 gas added to tank
May 7	300	

The lowest vapor pressure measured was 7 mm. This corresponds to a liquid nitrogen temperature of about 52°K. At the time this occurred the helium in the vacuum chamber had been evacuated, so the bar was more or less thermally isolated from the dewar and did not go below 60°K. More typically this pressure was 30 to 100 mm. The only attempt to control pressure was made by manually adjusting a ball valve daily to keep it somewhere in the above range. If the pressure dropped suddenly over a twenty four hour period, it was assumed that all the liquid nitrogen had boiled off. This happened shortly before Christmas about two months from the beginning of pumping and two and a half months from the last time liquid nitrogen was added.

The experiment was left unattended over the Christmas break during which the pressure of the water cooling the diffusion pump dropped, a thermostat cutoff failed, and all the diffusion pump oil boiled away. Returning from the break, we found the tank vacuum to be 20 microns and a bar temperature of 160°K After repairing the damage the dewar was again filled with liquid nitrogen and the system recooled. The experiment was kept about two weeks at 78°K to take more data and then cooled to the sixties again. After about two months the liquid nitrogen was again exhausted and the system was allowed to warm up. About 500μ of N_2 gas was added to the tank to speed warm up. After about three weeks room temperature was attained.

IV. EQUIVALENT CIRCUIT

The standard equivalent circuit for this system is



Z_1 represents circuit elements due to the fundamental mode of the bar, and Z_2 comes from the rigidity and dissipation of the cables and piezoelectric transducers. Z_3 is an external capacitor or resistor which was used in the measurement of the equivalent circuit. Unless otherwise stated, assume $Z_3 \to \infty$.

In practice $C_1 << C_2$ and $\omega L_1 >> R_1 + R_2$. The free oscillation frequency of the system, $\omega_o = 2\pi\nu_o$, is then given by,

$$\omega_o^2 = \frac{1}{L_1 C_1}$$

This frequency is measured by exciting the bar and attaching a frequency counter at the output. At frequencies away from ω_o, Z_1 is very much greater than Z_2. So Z_2 was measured with an A.C. bridge at a detuned ($\omega \neq \omega_o$) frequency.

The decay time of the system is determined by L_1 and the total dissipation. The total dissipation resistance is,

$$R_1 + R_2' \qquad\qquad Z_3 \neq \infty$$

with $$R_2' = \mathrm{Re}\left\{\frac{Z_3 Z_2}{Z_3 + Z_2}\right\}$$

When $Z_3 \to \infty$, $R'_2 \to R_2$. The bar was excited and the time for the signal to decay to one third, $\tau_{1/3}$, was measured with a stopwatch. $\tau_{1/3}$ was measured as a function of Z_3 and R'_2 was computed. We have the following relation:

$$R_2' = \left(\frac{2\ln 3}{\tau_{1/3}}\right) L_1 - R_1$$

Thus for several measured values of $\tau_{1/3}$ and Z_3, L_1 and R_1 can be determined from the slope and intercept of R_2' versus $\dfrac{2\ln 3}{\tau_{1/3}}$.

Given L_1 and ω_o, C_1 can be computed. The overall quality factor system, Q_1, is given by

$$Q_1 = \frac{\omega_o \tau_{1/3}}{2\ln 3}$$

The quality factor of Z_2 is given by,

$$Q_2 = \frac{1}{\omega_o C_2 R_2}$$

$\beta = \frac{C_1}{C_2}$ gives the fraction of the total energy which is observable in Z_2 for one cycle. βQ_1 is the traditional measure of energy observation efficiency.

Table II gives the measured values for the parameters described above. The first four columns were measured before Christmas, the last two after Christmas. Notice that L_1 is strongly dependent on temperature, a 30% decrease in temperature caused a 180% increase in L_1. L_1 is inversely proportional to the square of the coupling between the electrical and mechanical systems. This coupling is determined by the piezoelectric constant of the ceramics and the bonds between the ceramics and aluminum. An increase in L_1 means a decrease in coupling. Note that as coupling decreases, decay time increases, indicating that less energy is being dissipated by the transducer. Also the coupling deteriorated upon cycling up to 170°K and back down to liquid nitrogen temperature.

TABLE II

MEASURED PARAMETERS

Thermal						
Temp (°K)	78	60	62	64	78	66
L_1(Mh)	.46	1.3	1.03	1.3	1.7	3.2
C_1(pf)	.017	.006	.0077	.0061	.0047	.0025
R_1(kΩ)	23	38	30	43	61	88
C_2 (pf)	1300	1130	1140	1210	1500	1280
R_2(kΩ)	1.6	2.2	2.1	2.0	1.4	1.9
Q_1	250,000	370,000	360,000	370,000	310,000	430,000
Q_2	43	37	36	37	43	37
βQ_1	3.3	2.0	2.4	1.7	1.0	.8
ν_o(hz)	1778.8	1782.7	1782.6	1782.3	1778.3	1781.7
Period(μ sec)	562.19	560.95	560.98	561.06	562.32	561.25
$\tau_{1/3}$(sec)	49	72	71	72	61	84

V. NOISE TEMPERATURE

The top figure on the following page shows the overall electronics used to measure the noise temperature of the system. The following list describes the major electronic components:

Noise generator, Elgenco 602A

Preamp, tuned FET cascode with CP640 transistors

Postamp, four single tuned amplifiers cascaded

Butterworth filters, 2nd order with

τ_{BF} = .304, .40, or 1.85 sec.

Reference oscillator, 1.66 Mhz quartz crystal controlled oscillator with digital divide by n circuit

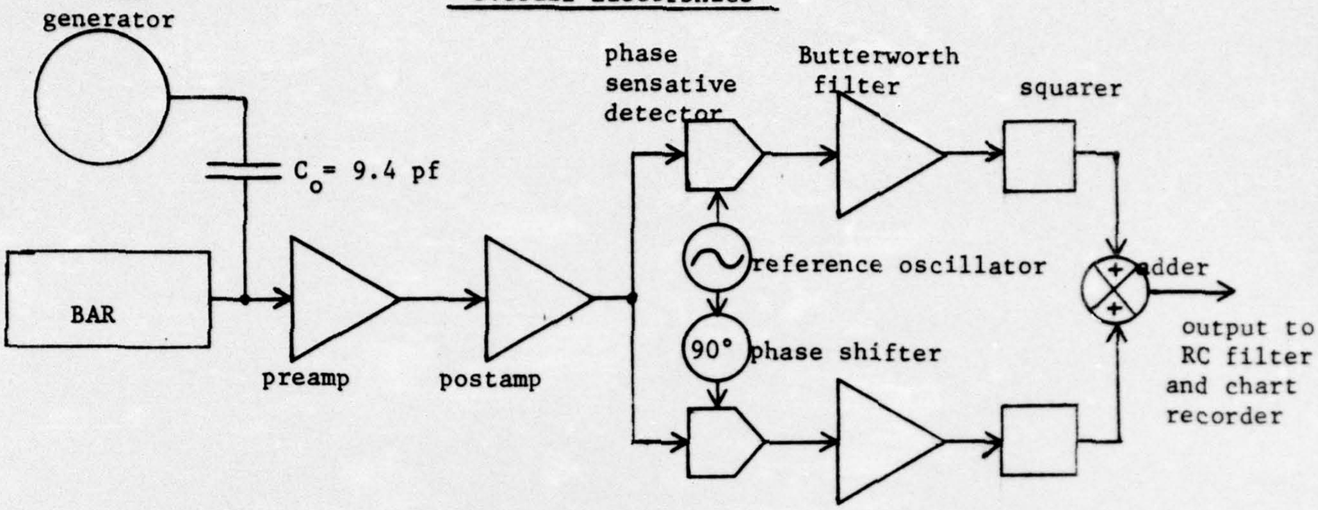
The overall output of the electronics is the mean square of the tuned amplification of the signal from the bar and noise generator. The center frequency is determined by the reference oscillator and the bandwidth by τ_{BF}. Let the center frequency gain be H_o and the effective noise bandwidth of the electronics be $\Delta\nu_a$.

The overall output when the reference oscillator is tuned to the bar and the noise generator is off is due to noise from the bar, ceramic transducers, and input to the preamp. If i is the current in the Z_1Z_2 loop, then the equipartition theorem gives,

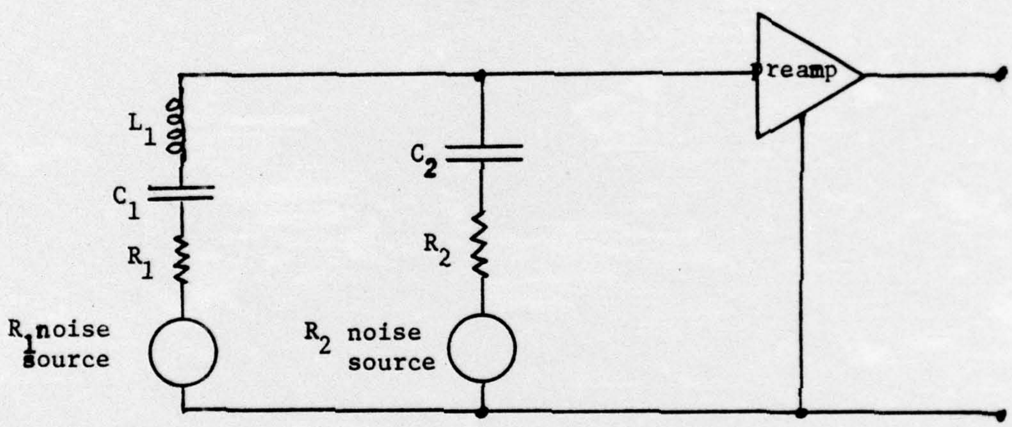
$$\langle i^2 \rangle = \frac{kT}{L_1}$$

This noise current will be concentrated in the noise bandwidth of the bar, $\Delta\nu_b = (2\tau_{1/3}\ell n3)^{-1} \approx 10^{-2}$ hz. Since $\Delta\nu_a$ = .2 to 1 hz, all the voltage produced by this noise current going through Z_2 will be amplified.

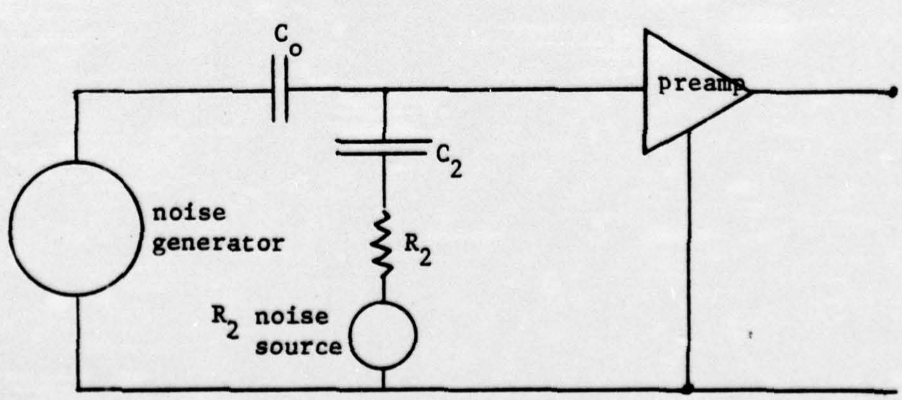
Overall Electronics



Tuned Circuit



Detuned Circuit



So the bar contribution to the overall output voltage is,

$$v_b^2 = |H_o|^2 \, |Z_2|^2 \, \frac{kT}{L_1}$$

This voltage will be added to the voltage noise produced by the ceramic and preamp,

$$v_c^2 = |H_o|^2 \{ 4kTR_2\Delta\nu_a + v_n^2 \}$$

The wideband preamp noise, v_n^2, was due to both current and voltage sources and was roughly a third or less of the ceramic noise. It is convenient to put the two together. The net result is,

$$v_{bc}^2 = v_b^2 + v_c^2 = |H_o|^2 \{ (\frac{1}{\omega_o^2 c_2^2} + R_2^2) \frac{kT}{L_1} + 4\, kTR_a\Delta\nu_a + v_n^2 \}$$

The above is not quite correct because the loop current and the R_2 Johnson noise are not independent noise sources. When one actually does the integrals using the Johnson noise of R_1 and R_2 as independent voltage sources and assumes $\Delta\nu_b \ll \Delta\nu_a$, then the above result is reproduced with a minus sign in front of R_2^2. This more rigorous result also includes a so called "antiresonance effect" where within the narrow bandwidth of the bar Z_1 becomes comparable with Z_2 and thus causes a small drop in the R_2 noise voltage at the preamp input. However since $1/\omega_o^2 c_2^2 \gg R_2^2$ we can neglect the latter in our calculations. When evaluating the noise integrals the $\Delta\nu_b \ll \Delta\nu_a$ assumption produces errors of order $\Delta\nu_b / \Delta\nu_a = .01$ to $.03$.

When the reference oscillator is detuned from the bar frequency by about a hertz, we no longer see the bar noise current, however v_c^2 is still present. The noise generator is used in the detuned circuit as a calibrating current source. It produces an overall output of

$$v_g^2 = |H_o|^2 \left(\frac{c_o}{c_2}\right)^2 S\Delta\nu_a \qquad \text{for } c_o \ll c_2$$

where S is the spectral density of the noise generator. The total detuned output is then,

$$v_{gc}^2 = v_g^2 + v_c^2 = |H_o|^2 \left\{\left(\frac{c_o}{c_2}\right)^2 S\Delta\nu_a + 4kTR_2\Delta\nu_a + v_n^2\right\}$$

The major part of the noise temperature measurement is the measurement of the three numbers v_{bc}^2, v_{gc}^2, and v_c^2. Each is recorded on the chart recorder for at least half an hour up to several hours and a numerical average is made. Using these to eliminate $|H_o|^2$ and $4kTR_2\Delta\nu_a + v_n^2$ in the above equations we obtain,

$$r \equiv \frac{v_{bc}^2 - v_c^2}{v_{gc}^2 - v_c^2} = \frac{kT}{L_1\omega_o^2\, c_o^2 S\Delta\nu_a} \equiv \frac{T}{T_o}$$

The total rms voltage of the noise generator, v_{gen}, was read from a meter on the chassis. The manual for this device gives the spectral density of the output as approximately 25 $(mv)^2$ per hertz, when v_{gen} = 1 volt, uniform to ± 1 dB to 20 Khz. Two measurements of this quantity at 1800 hz gave 23 and 27. Thus the spectral density of the noise generator can be given by,

$$S = \frac{v_{gen}^2}{\nu_{gen}} \quad \pm\ 8\%$$

where ν_{gen} = 40,000 hz. The effective noise bandwidth for a "lockin" amplifier with second order Butterworth filters is,

$$\Delta\nu_a = \frac{1}{2\pi}\int_{-\infty}^{\infty}\frac{d\omega}{1+(\omega\tau_{BF})^4} = \frac{1}{2\sqrt{2}\,\tau_{BF}}$$

τ_{BF} can be calculated from the circuit elements of the device. As a check of this, the noise bandwidth of the amplifier was measured and found to agree reasonably (5%) with the above.

The noise temperature of the bar is then given by,

$$T_N = r\,T_o = \left(\frac{v_{bc}^2 - v_c^2}{v_{gc}^2 - v_c^2}\right)\left(\omega_o^2 c_o^2\,\frac{L_1 v_{gen}^2}{k\nu_{gen}}\,\Delta\nu_a\right)$$

Large amounts of noise, greatly exceeding what is expected for a system in thermal equilibrium, were observed whenever the cylinder was not in equilibrium. The normal mode frequency of the cylinder is temperature dependent.

The rate of drift of the normal mode frequency was a measure of the approach to an equilibrium state. For measurements reported here the rate of drift of the mean cylinder temperature was less than

$$.01\ \frac{^\circ K}{\text{day}}$$

Table III shows the results of noise temperature measurements. The most important thing to note is that the values for T_N are the same as the thermal temperatures to within a factor of about 2. This is a considerable improvement over a previous cryogenic experiment (liquid helium) where noise temperatures of tens of thousands of degrees were measured. However, this factor of 2 is larger than the expected

TABLE III

DATA FOR NOISE TEMPERATURE

Date of Measurement	Aug. 16	Aug. 18	Aug. 22	Aug. 25	Nov. 12	Nov. 26	Dec. 2	Dec. 10
Thermal Temp. (°K)	78	78	78	78	62	62	64	64
L_1 (Mh)	.46±3%.	.46±3%.	.46±3%	.46±3%	1.03±8%	1.03±8%	1.3±8%	1.3±8%
ν_o (hz)	1779	1779	1779	1779	1782	1782	1782	1782
r	.82±6%	.30±12%	.79±10%	.67±6%	.38±12%	.40±15%	.71±11%	.54±9%
$\Delta\nu_a$ (hz)	1.16	1.16	.89	.89	.20	.20	.20	.20
v_{gen} (10^{-4}volts)	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5
τ_{BF} (sec)	.304	.304	.41	.41	1.85	1.85	1.85	1.85
T_o (°K)	106	106	82	82	93	93	116	116
T_n (°K)	87±10%	32±15%	64±13%	55±10%	35±16%	37±19%	82±16%	63±14%

Date of Measurement	Jan.23	Jan.27	Jan.29	Feb. 1	Feb. 2	Feb. 3	March 17
Thermal Temp (°K)	78	78	78	78	78	78	66
L_1 (Mh)	1.7±3%	1.7±3%	1.7±3%	1.7±3%	1.7±3%	1.7±3%	3.2±6%
ν_o (hz)	1779	1779	1779	1779	1779	1779	1782
r	.83±17%	.91±6%	.49±10%	.69±6%	.84±6%	.73±5%	1.15±6%
$\Delta\nu_a$ (hz)	.20	.20	.20	.20	.20	.20	.20
v_{gen} (10^{-4}volts)	1.5	1.5	1.5	1.5	1.5	1.5	1.0
τ_{BF} (sec)	1.85	1.85	1.85	1.85	1.85	1.85	1.85
T_o (°K)	152	152	152	152	152	152	125
T_n (°K)	126±19%	138±10%	74±13%	105±10%	128±10%	111±10%	143±12%

error of 10 to 15%. The largest known sources of error are from L_1, r, and S. These are all included in the estimated error of T_N. The question is, are the differences between the thermal and noise temperatures due to excess noise? Excess noise cannot produce a total noise temperature less than the thermal temperature, but this was observed several times by a factor of 1/2. There must be an unaccounted source of error to produce this effect. It is not known what this error was. One can speculate that perhaps the quality of the bonds between the transducers and the bar fluctuated, maybe there was an aging effect. For a given temperature L_1 was measured once or twice and then used in measurements of T_N even though they were one or two weeks later. However $\tau_{1/3}$ was also an indication of coupling as seen before, and daily measurements of it at a given temperature did not show any significant fluctuations, i.e. < 2%. It is felt that the error is still due somehow to the transducer.

VI DISCUSSION

The cryostat held a vacuum and liquid nitrogen well. The last time liquid nitrogen was added was January 16. It required nearly three months for the liquid nitrogen to boil away. In fact during part of this time, the vacuum tank contained helium and the system was cooled from 78°K to 62°K. So left alone, the liquid nitrogen probably would have lasted more than three months.

Thermal equilibrium was obtained in the bar after less than a few weeks. The first noise measurement was made after the bar had been below 80°K for three weeks and below 300°K for six weeks. Similar results were obtained when cooling to the sixties and when cycling up to 170°K and down again. Unfortunately, the overall accuracy of the noise temperature was only ± 50%. No excess noise was observed above this level with the exception of what will be described next.

An interesting noise phenomenom occurred after cooling down to 60°K the first time. The background noise was observed on the chart recorder to be about a tenth of full scale. However, one to five times an hour the signal would go full scale for several minutes. This was not observed at 78°K. The pumps were turned off and the valve to the cryostat closed to see if there was acoustic noise from the pumps. There was no immediate effect, but three hours later all this excess noise suddenly stopped. For a day afterwards only a couple of spikes occurred. From the pressure of the dewar the temperature of the nitrogen must have been in the lower fifties. The freezing point is 63°K, so all the nitrogen must have been flozen solid. The following explanation is given. While pumping on solid nitrogen pressure gradients in the solid cause large amounts of noise. We had a

non-equilibrium situation with the surface temperature $\approx 52°K$ and with other parts of the solid nitrogen at higher temperatures and vapor pressures. Several hours after pumping ceased equilibrium was approached close enough so that the stresses no longer produced visible noise. It was decided to let the dewar warm up to melt the nitrogen and eliminate this problem. So the valve to the cryostat was left closed. During this warmup, there were periods of quiet and of noise. When the pressure of the dewar was about 90mm, about the triple point pressure, there was an intense burst of noise lasting about seven hours and sudden quiet afterwards for days. This was presumably due to noise from the nitrogen actually melting.

With the exception of the solid nitrogen effect acoustic noise did not significantly add to the overall background noise. However, the detector was sensitive to individual acoustic events such as knocking on the tank and closing doors. A quieter location and more acoustic isolation will be helpful.

pzt-8 was mistakenly used for the transducer. It was known that the piezoelectric coupling for such ceramics decreases at cryogenic temperatures. We did get lower than expected βQ's. pzt-1 should have been used instead.

It was noted that the coupling between the bar and the transducer decreased upon cycling up to 170°K and down again. This was probably due to weakening of the polyurethane rubber bonds holding the transducer together and to the bar.

The largest observed decay time for an eight inch bar at room temperature was about 60 seconds, weakly loaded. The measured decay time of 84 seconds demonstrates decreased dissipation in aluminum at cryogenic

temperatures. Indeed, Carelli et al.[3] have measured Q's of greater than a million for aluminum at liquid helium temperatures. With a less lossy transducer than piezoelectric ceramics on the bar, we look forward to significantly increased Q's when liquid helium operation is attained.

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[3] Carelli, P., et al. "Q Measurements Down to Liquid Helium Temperatures for a Gravitational Wave Aluminum Bar Antenna," Cryogenics, July 1975.

VII. FUTURE OPERATIONS

The real goal of this project is to run the experiment at liquid helium temperature. The cryostat is now being moved to a quieter location where a CTI 1400 helium liquifier/ refrigerator is installed. Since we do not presently have a helium recovery system or facilities to store large amounts of gas, the machine will be run as a refrigerator. The refrigerator and cryostat will be run closed loop with gas added as temperatures go down.

In the liquid nitrogen experiment gas was added to the common vacuum to increase thermal conductivity between the bar and the dewar. This also increases **the other thermal couplings, and at** liquid helium temperatures will be too inefficient. Copper plates soldered to the ends of the dewar will isolate the bar space from the vacuum of the superinsulation. The seal there does not have to be perfectly leak tight, because there will only be a couple microns pressure difference.

After liquid helium temperatures have been attained with the refrigerator, a determination of the state of the bar and transducer and of the performance of the cryostat and acoustic isolation will be made. If these prove satisfactory, then 150ℓ of liquid helium will be purchased to fill up the dewar. Since at one atmosphere it requires approximately two thirds as much heat to bring one liter of liquid helium from 4°K to 300°K as it does for a liter of liquid nitrogen from 77°K to 300°K , one would expect to hold helium in the dewar about two months.

In order to improve the turn around time we really need to decrease the one month it takes to warm up. Two ways have been considered, electric heaters on the dewar and circulating warm helium gas through the cryostat.

Further improvements in the cryostat will come by adding more temperature sensors, a reliable thermostat cutoff for the diffusion pump, and some modifications in the plumbing to allow separate or combined evacuation of the two vacuum spaces.

Piezoelectric ceramics on the top of the bar will be removed. This will allow room for another stage of felt-iron acoustic isolation.

The DC capacitor transducer developed by J.P. Richard[4] will replace the piezoelectric ceramics. It has already been tested at room temperature and found to have a βQ of ~ 100 with an eight inch bar. These measurements indicate that the sensor will be able to easily measure 4°K noise.

4. Richard, J-P., ibid.